INNOVATIVE THERMAL MANAGEMENT OF FUEL CELL POWER ELECTRONICS

Kenneth J. Kelly, Desikan Bharathan

National Renewable Energy Laboratory

Andreas Vlahinos

Advanced Engineering Solutions

Pablo Rodriguez

Ballard Power Systems

Electric Drives and Power Conversion Division

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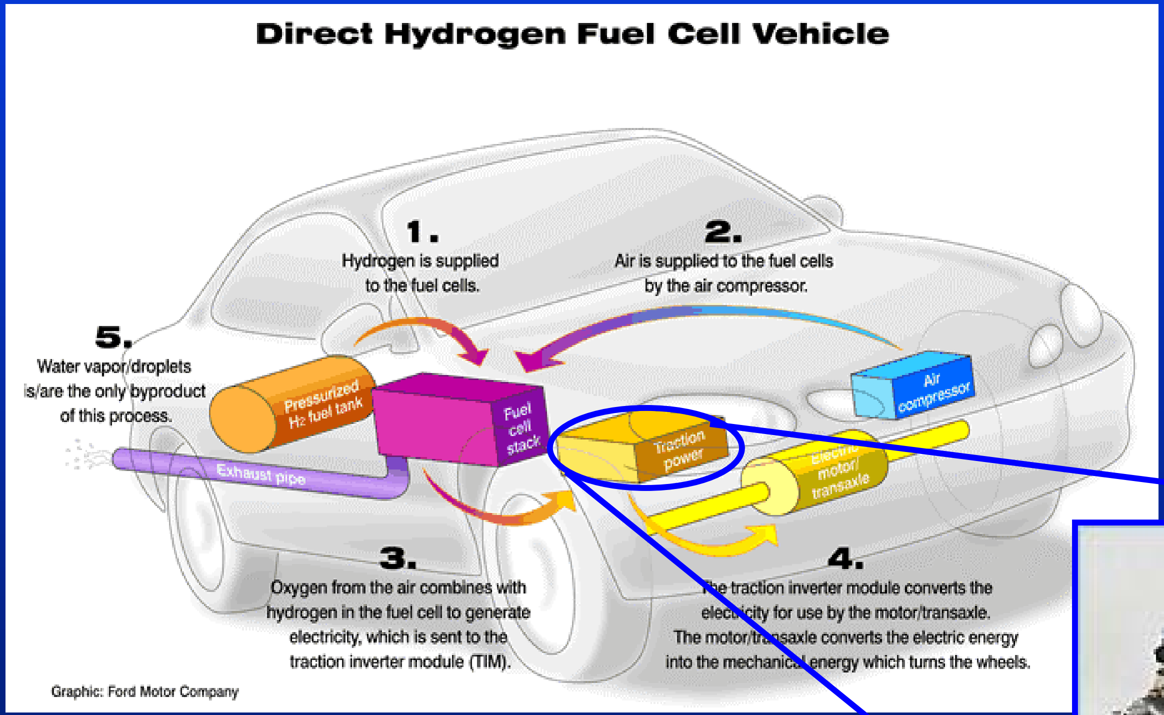
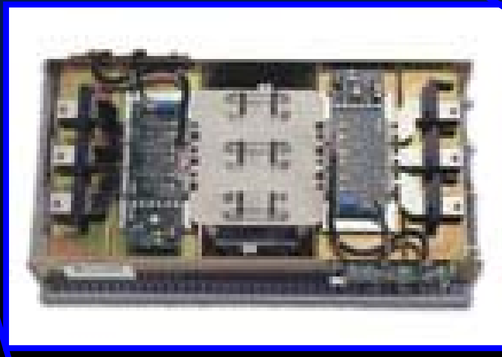
Power Electronics Cooling

Critical Enabling Technology for Fuel Cell Vehicle and Stationary Applications

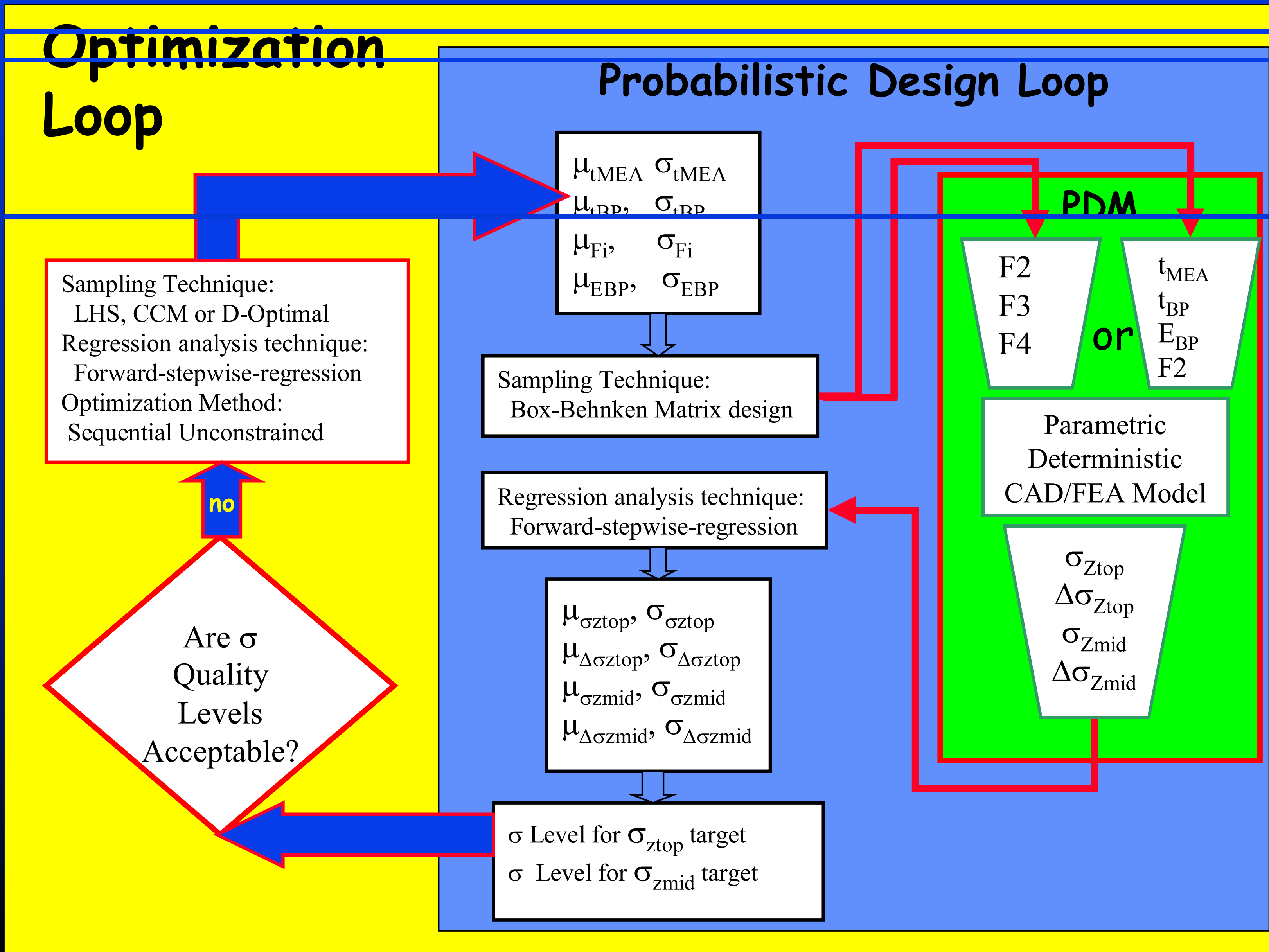




Project Goal :

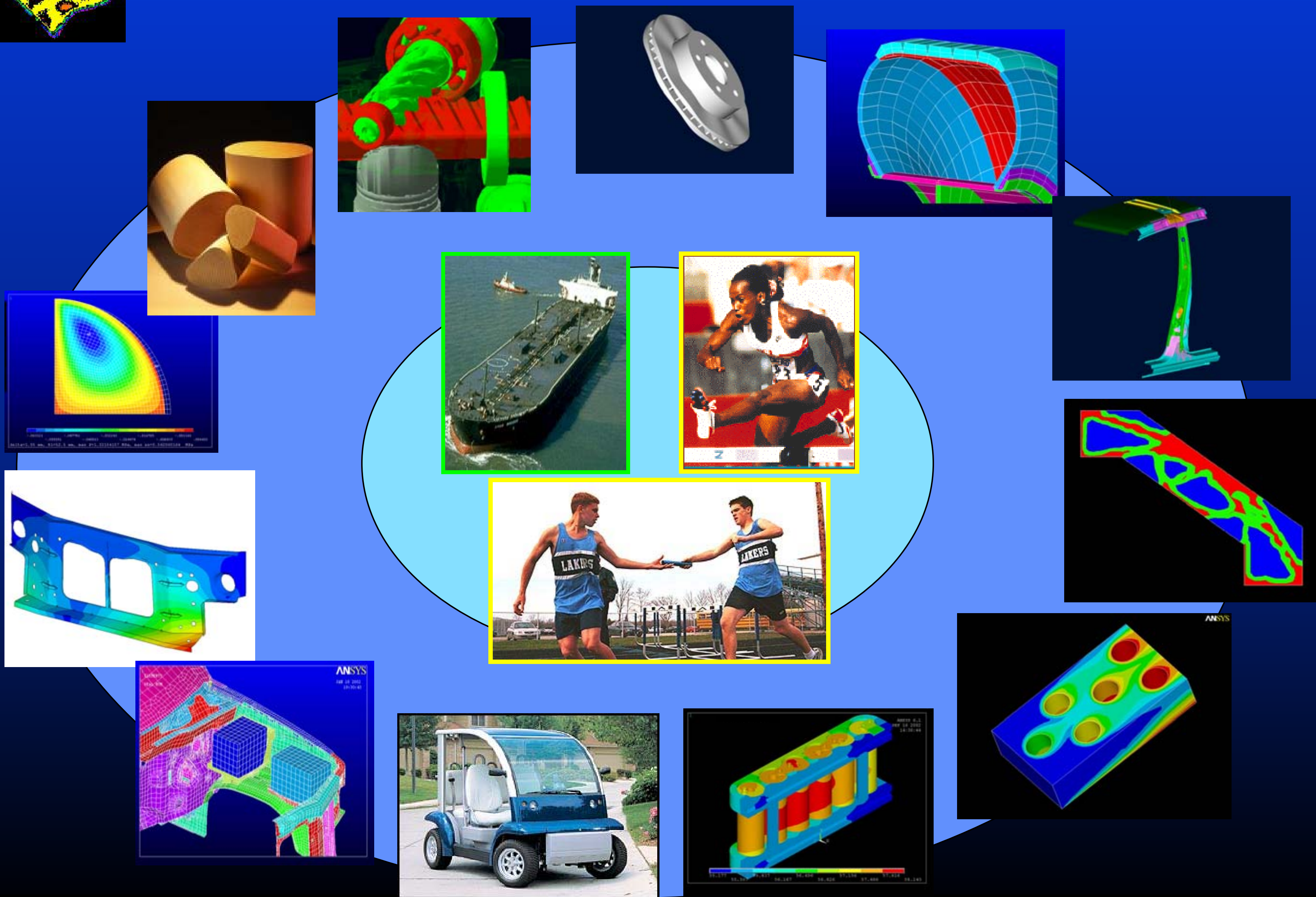
Develop a heat exchanger design to efficiently remove heat from the power module and reject it into the vehicles coolant loop with uniform cooling, minimum cost, volume and pressure drop.

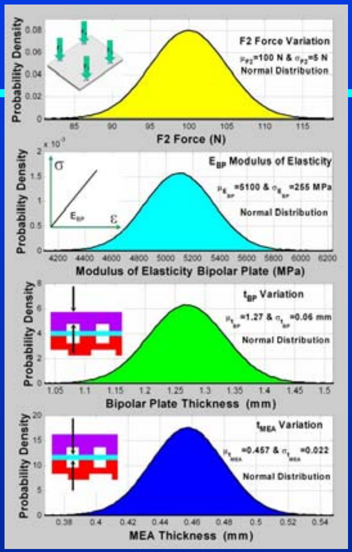
Robust Optimization reusable workflow template



Background: Recent DFV Applications

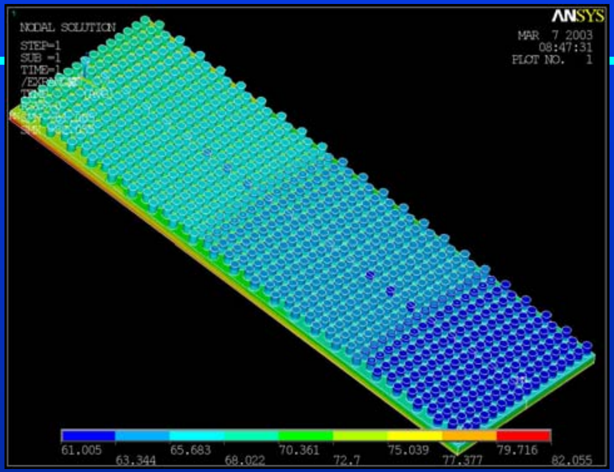
Petroleum Consumption, Technical Hurdles, Transfer to Industry



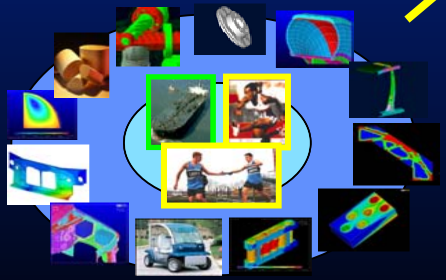


Robust Designs of Fuel Cell Components

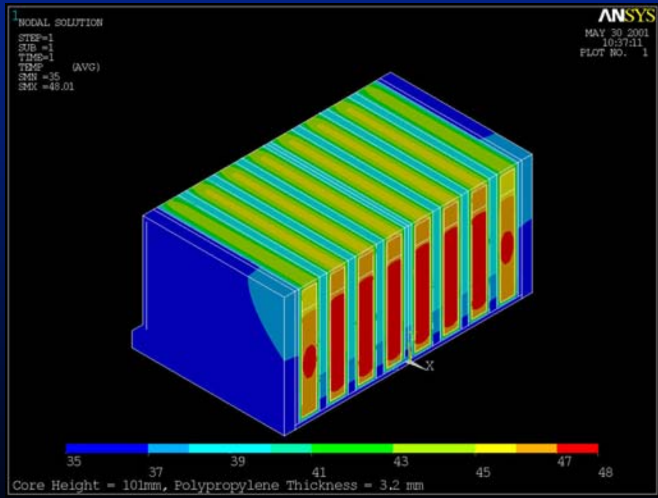
- *Thermal analysis*
- *Structural analysis*
- *Topology optimization*
- *High temperature stack*



Behavioral Modeling for Power Electronics Cooling

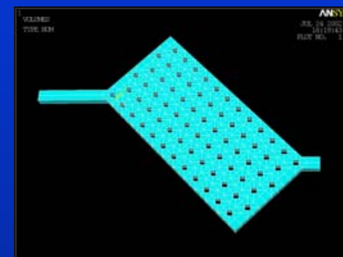


Design for Six-sigma Techniques for Battery Thermal Management



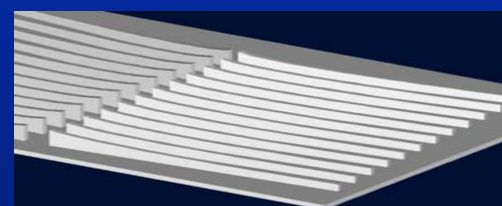
Review of Literature and Conceptual Designs

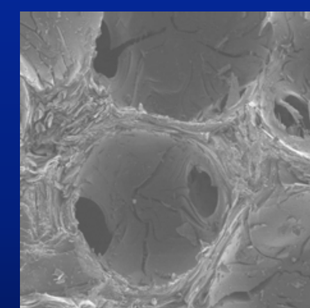
1. Pin-Finned Design



2. “Cook-top” serpentine flow field

3. “Fish bone” fins





4. Carbon Foam
5. Aluminum Extrusion with Expanded Metal Turbulator

Review of Literature and Conceptual Designs

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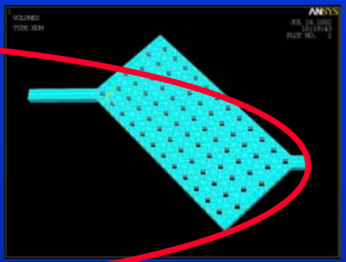

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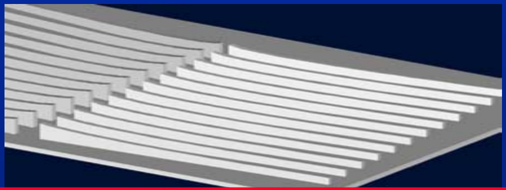
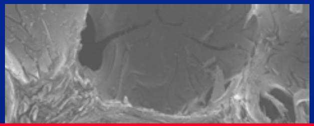




4. C

5. Al

Tu

Liquid Cooled, Integrated Pin-fin heat exchanger

- **Low Cost**
- **Compact**
- **Effective**
- **Durable**

Problem Statement

Develop a workable methodology to find the optimal pin-fin geometry that:

Minimizes **dT**

Where:

1 mm	<	Pin_dia	<	10 mm
1 mm	<	Pin_h	<	5 mm
1	<	Nx	<	15 (integer)
2	<	Ny	<	50 (integer)

Subject to:

maxT	<	125 °C
dP	<	20000 Pa
(Lx-Nx*Pin_dia)/Nx	>	0.5 mm (no interference in x)
(Ly-2*Ny*Pin_dia)/(2*Ny)	>	0.5 mm (no interference in y)

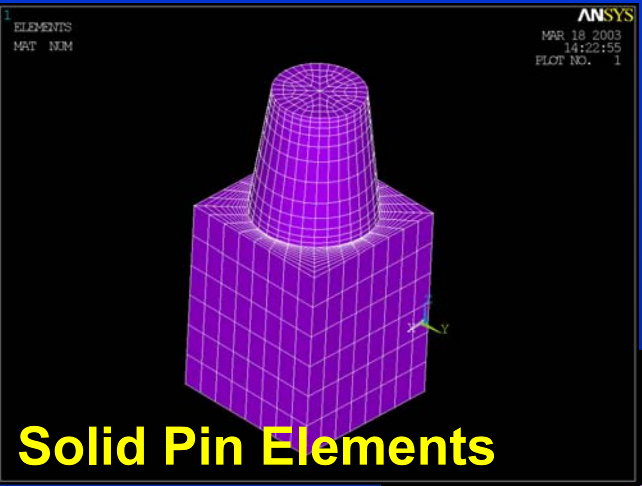
Input Parameters and Assumptions

- Heat Exchanger Base and Pins - AlSiC
  - Thermal conductivity ($k = 150$ W/mK)
  - Density ($\rho = 3000$ kg/m^3)
  - Heat Capacity ($C = 768$ J/kg C)
- Coolant - Water
  - Thermal conductivity ($k = 0.66$ W/mK)
  - Density ($\rho = 983$ kg/m^3)
  - Heat Capacity ($C = 3000$ J/kg C)

- Boundary Conditions:
  - Heat Flux ($q = 80$ W/cm^2)
  - Coolant Flow Rate ($u = 1.4 \times 10^{-4}$ m^3/s)
  - Inlet Temperature: ($T_{in} = 60$ °C)
  - Symmetry along the "y" plane (along flow path)

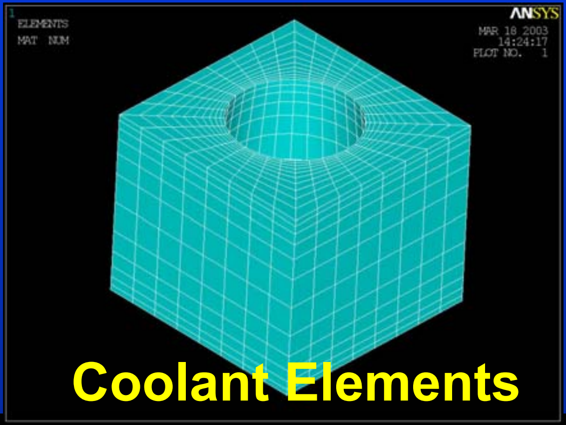
- Material behavior isotropic

FEA Model – CFD Analysis of Pin Fin Design

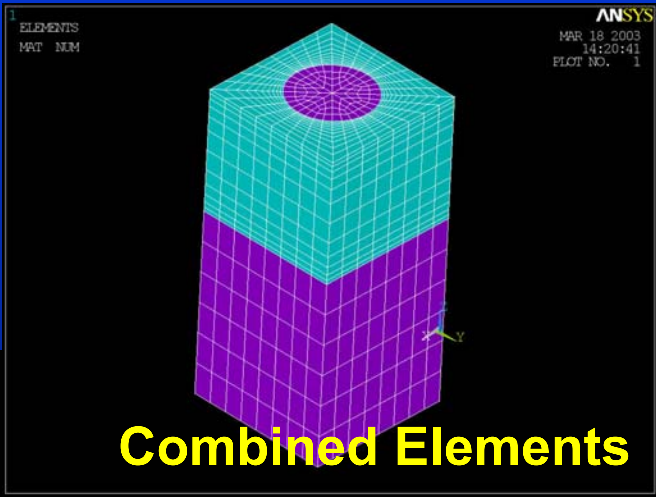


Solid Pin Elements

Elements 3648
Nodes 4387

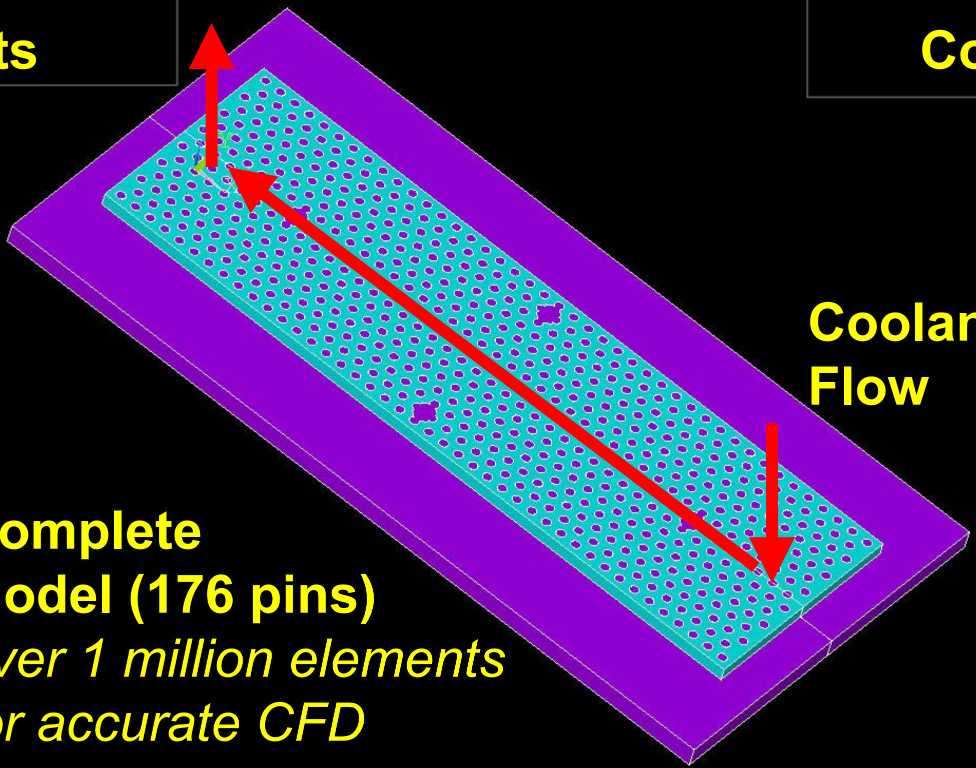


Coolant Elements



Combined Elements

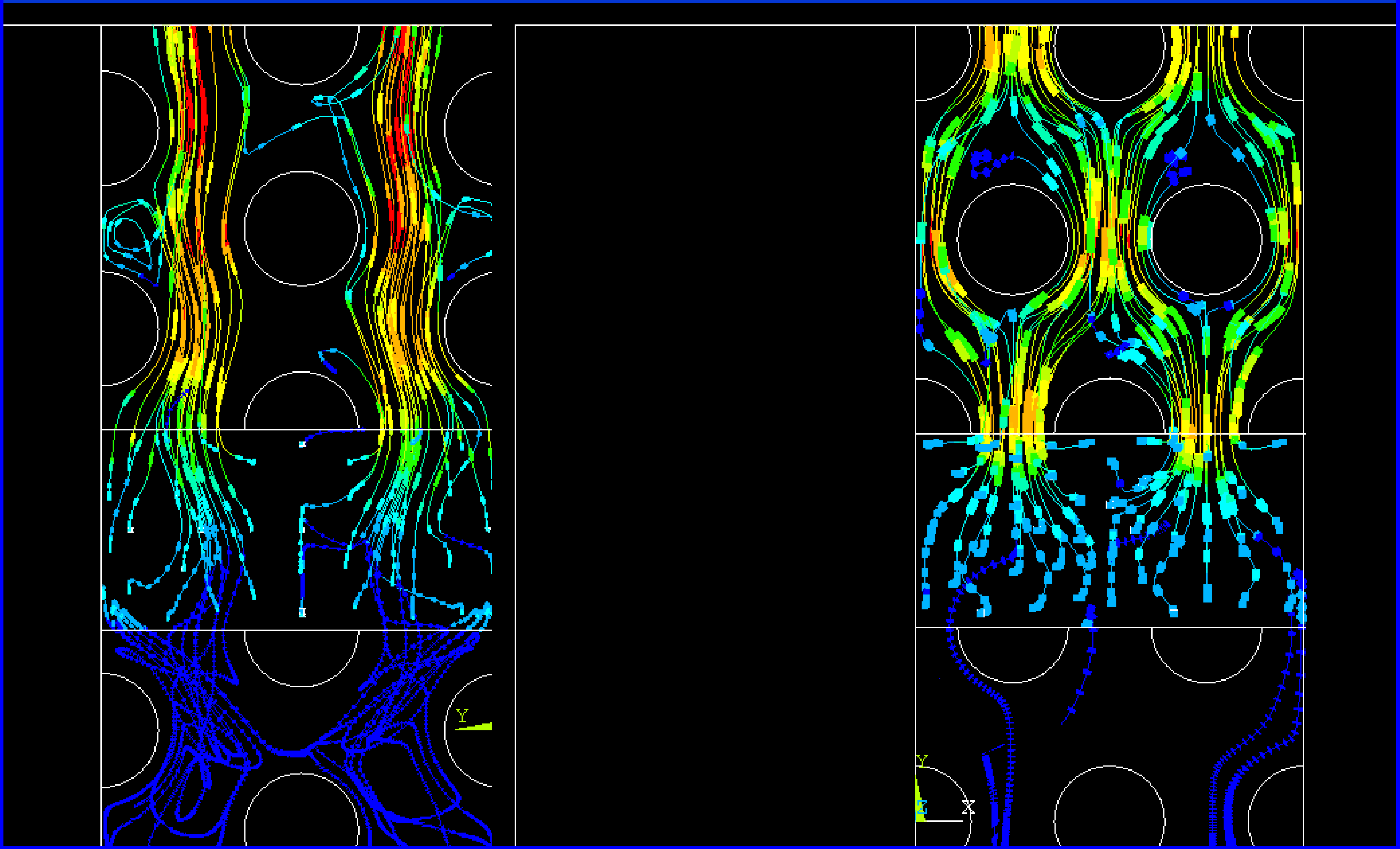
Elements 7488
Nodes 8227



Coolant Flow

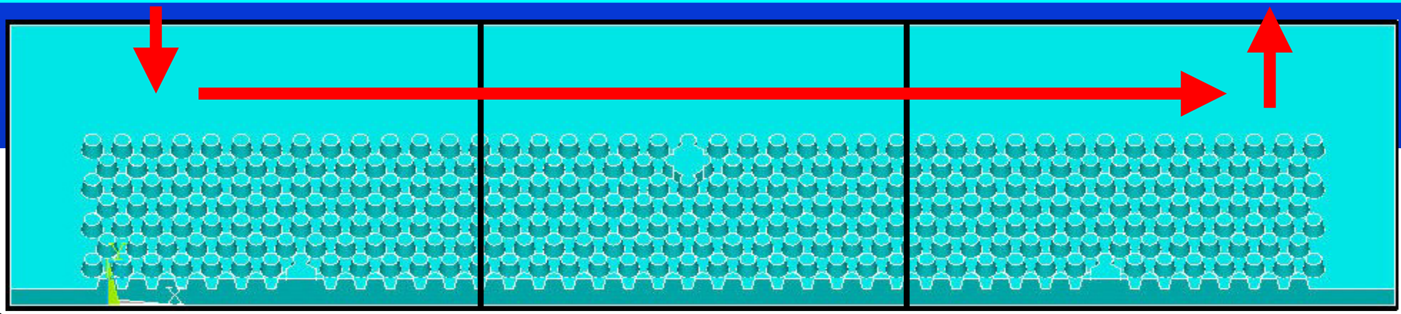
Complete Model (176 pins)
over 1 million elements for accurate CFD

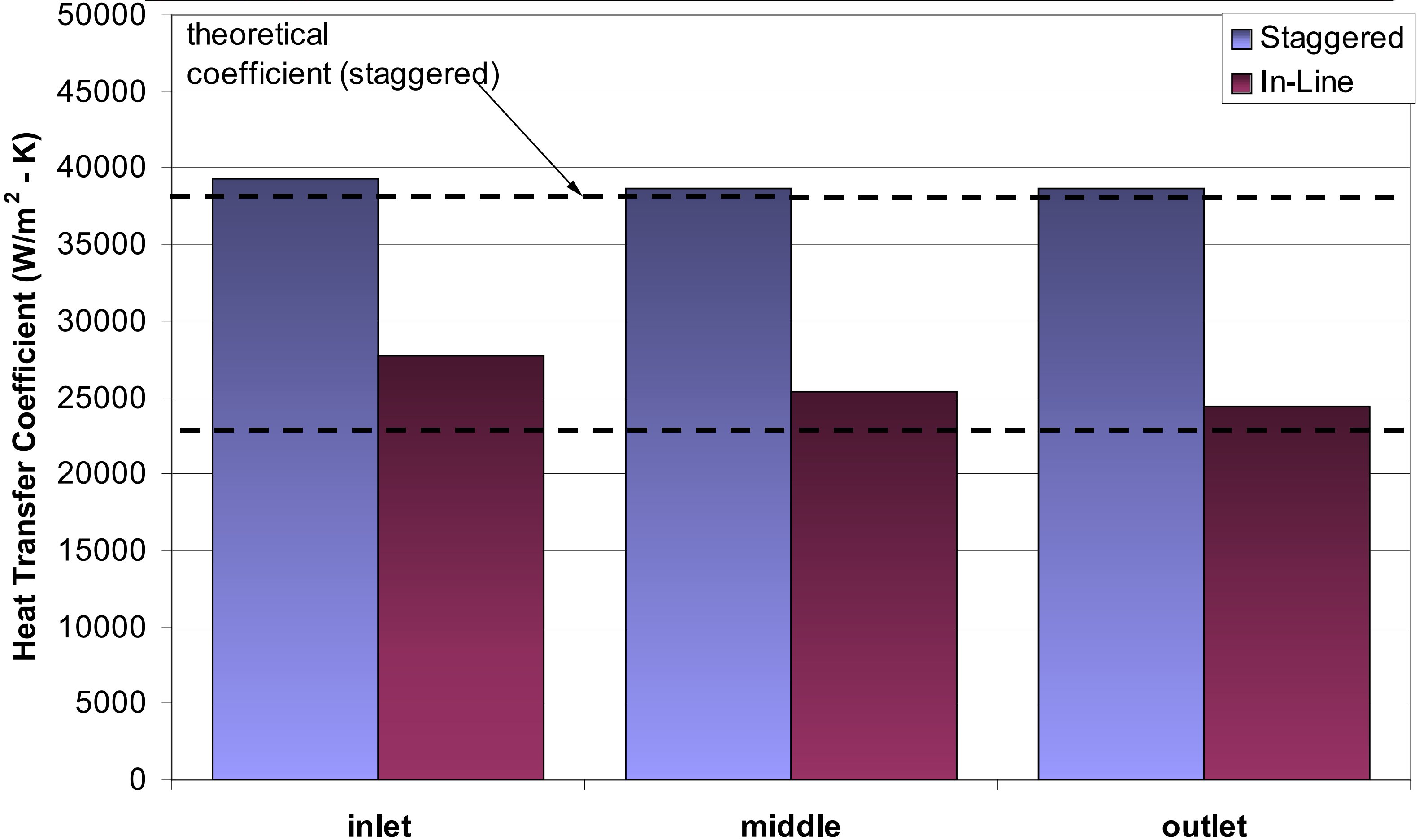
CFD Analysis of Staggered vs. In-Line Flow



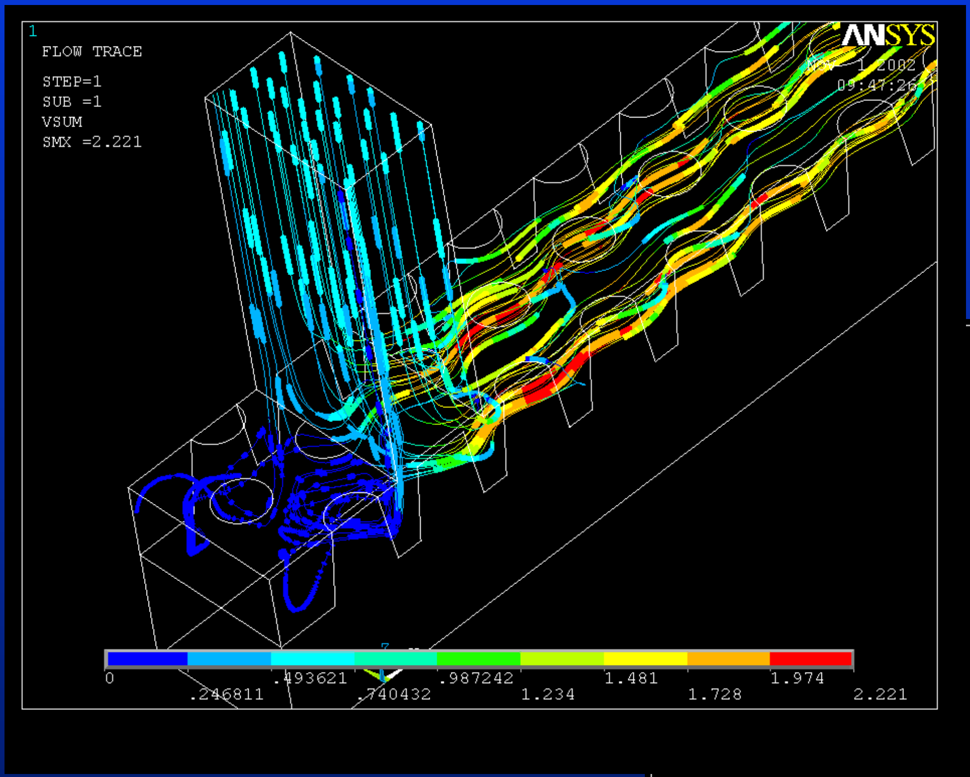
Heat Transfer Coefficient from CFD Analysis

Staggered vs. In-Line Flow

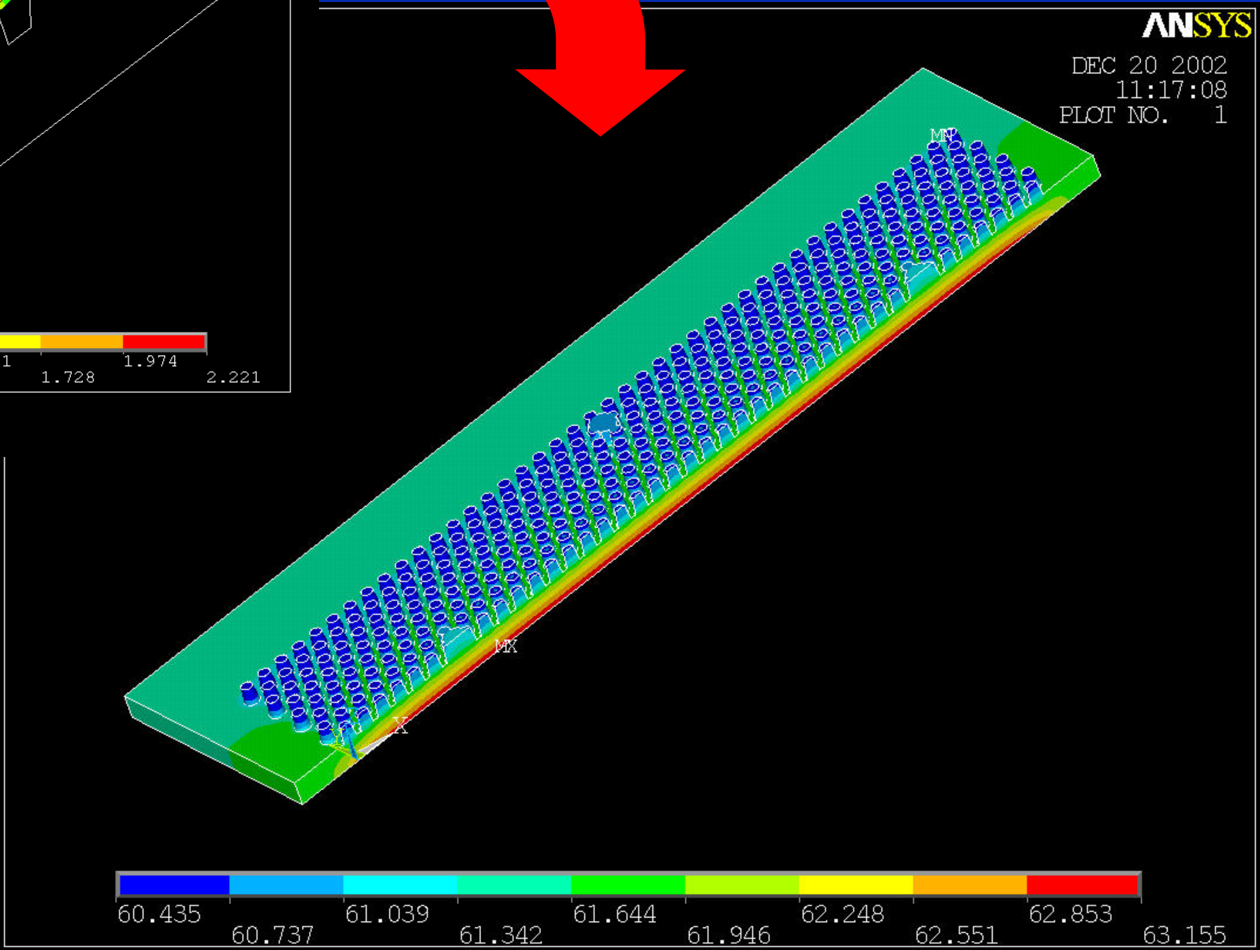




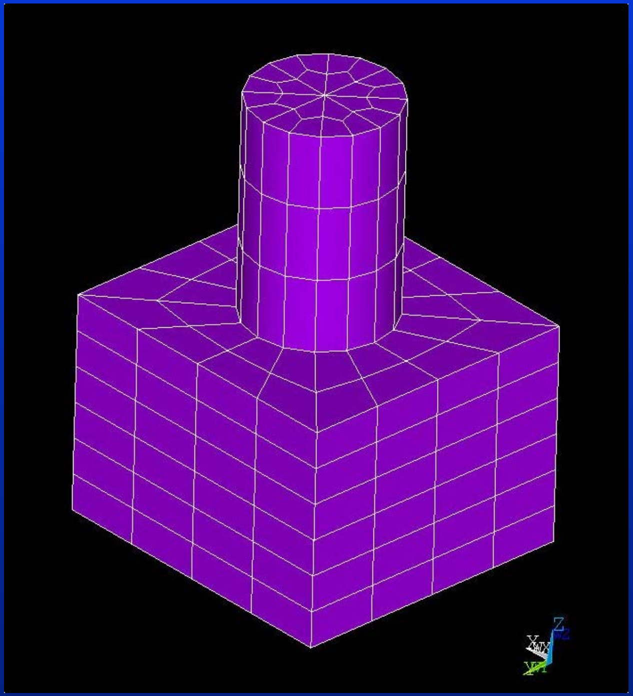
Conjugate Solution of CFD and Heat Transfer

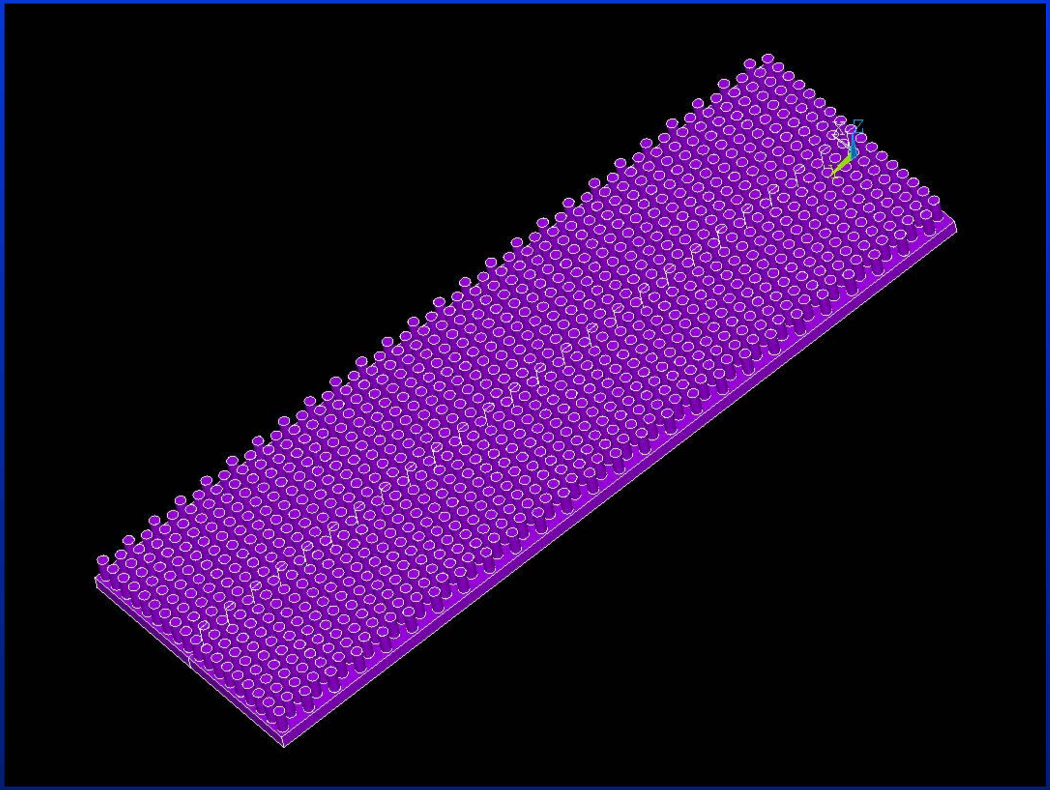


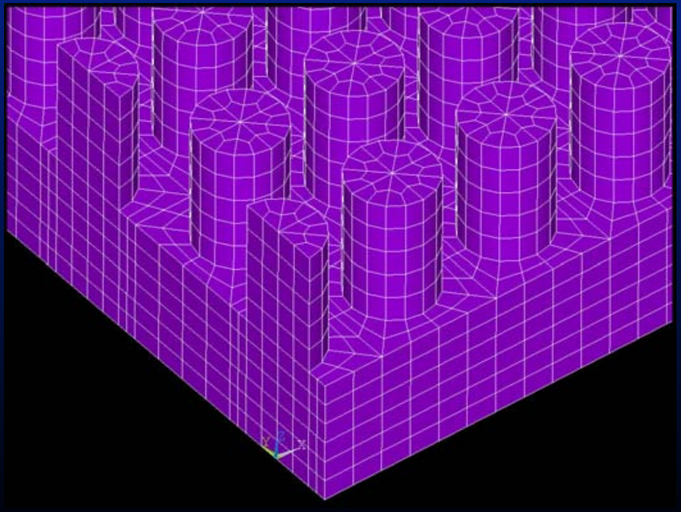
Thermal Analysis Using Film Coefficients Derived from CFD



Thermal FEA Model





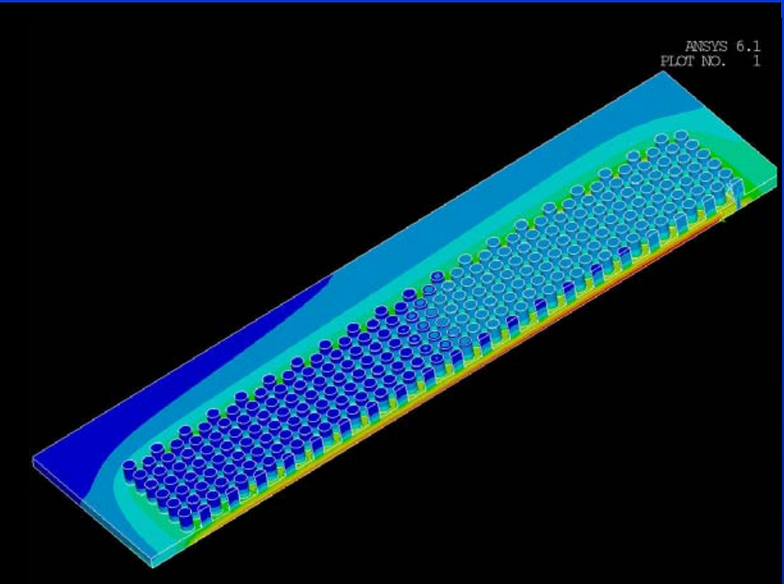


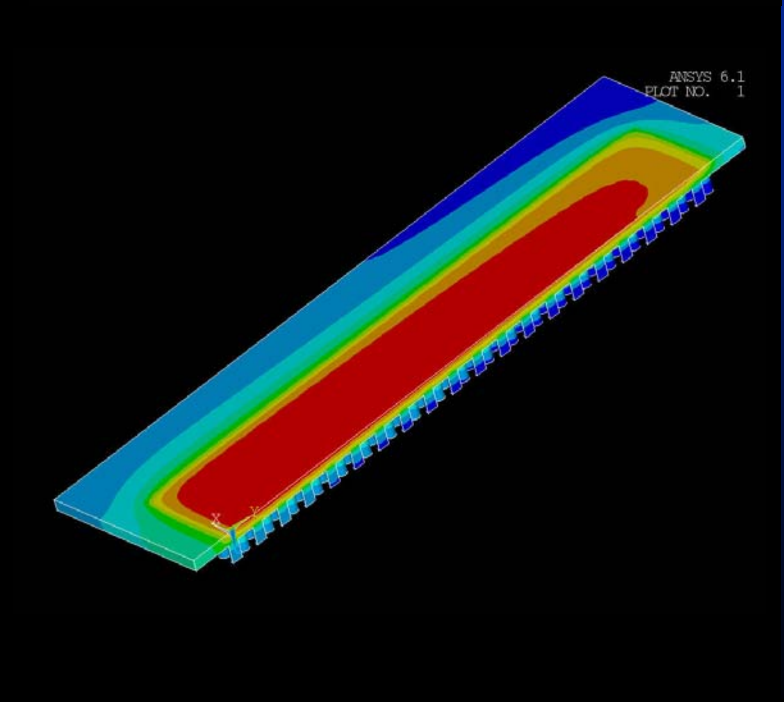
Elements: 480 per pin
Nodes: 653 per pin

176 pin model: 82K elements
100K nodes

Thermal Analysis

with Classical Theoretical Determination of Film Coefficients (Kreith)





Reynold's number for flow around pin fins

$$\mathrm{Re}_D = \frac{U_{\max} D}{\nu}$$

Nusselt number

- laminar

$$Nu_D = 0.9\,\mathrm{Re}_D^{0.4}\,\mathrm{Pr}^{0.36}$$

- transitional

$$Nu_D = 0.35\left(\frac{St}{Sl}\right)^{0.2}\mathrm{Re}_D^{0.6}\,\mathrm{Pr}^{0.36}$$

- turbulent

$$Nu_D = 0.022\,\mathrm{Re}_D^{0.84}\,\mathrm{Pr}^{0.36}$$

Heat transfer coefficient

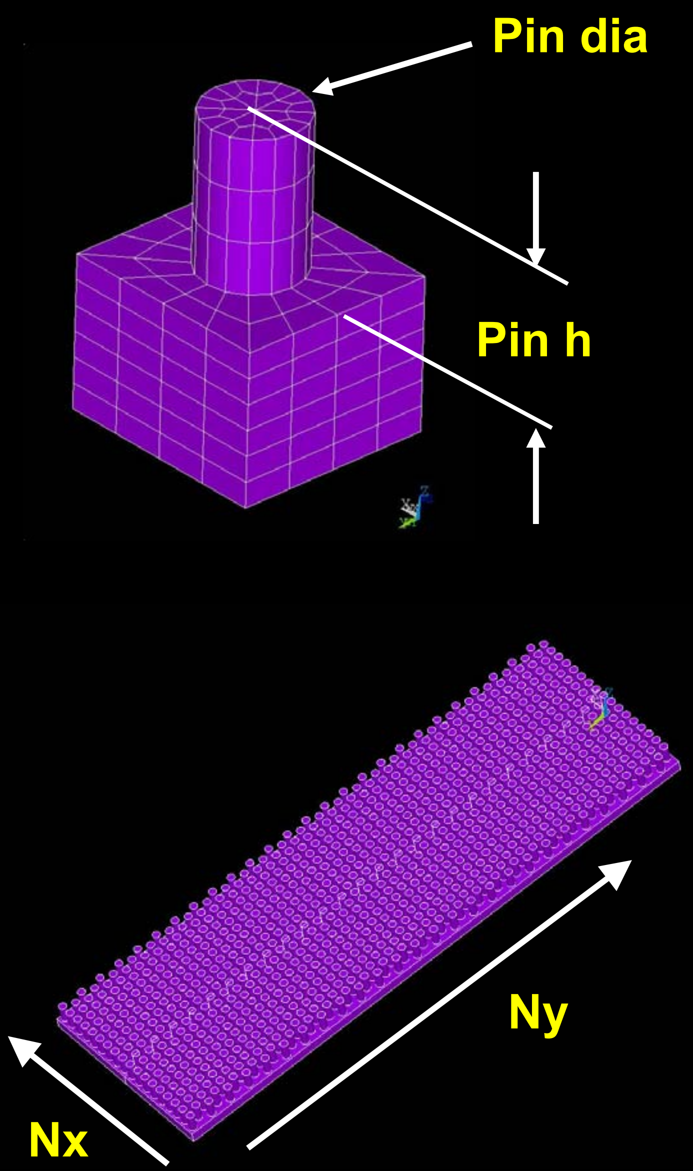
$$h = \frac{Nu \times k}{D}$$

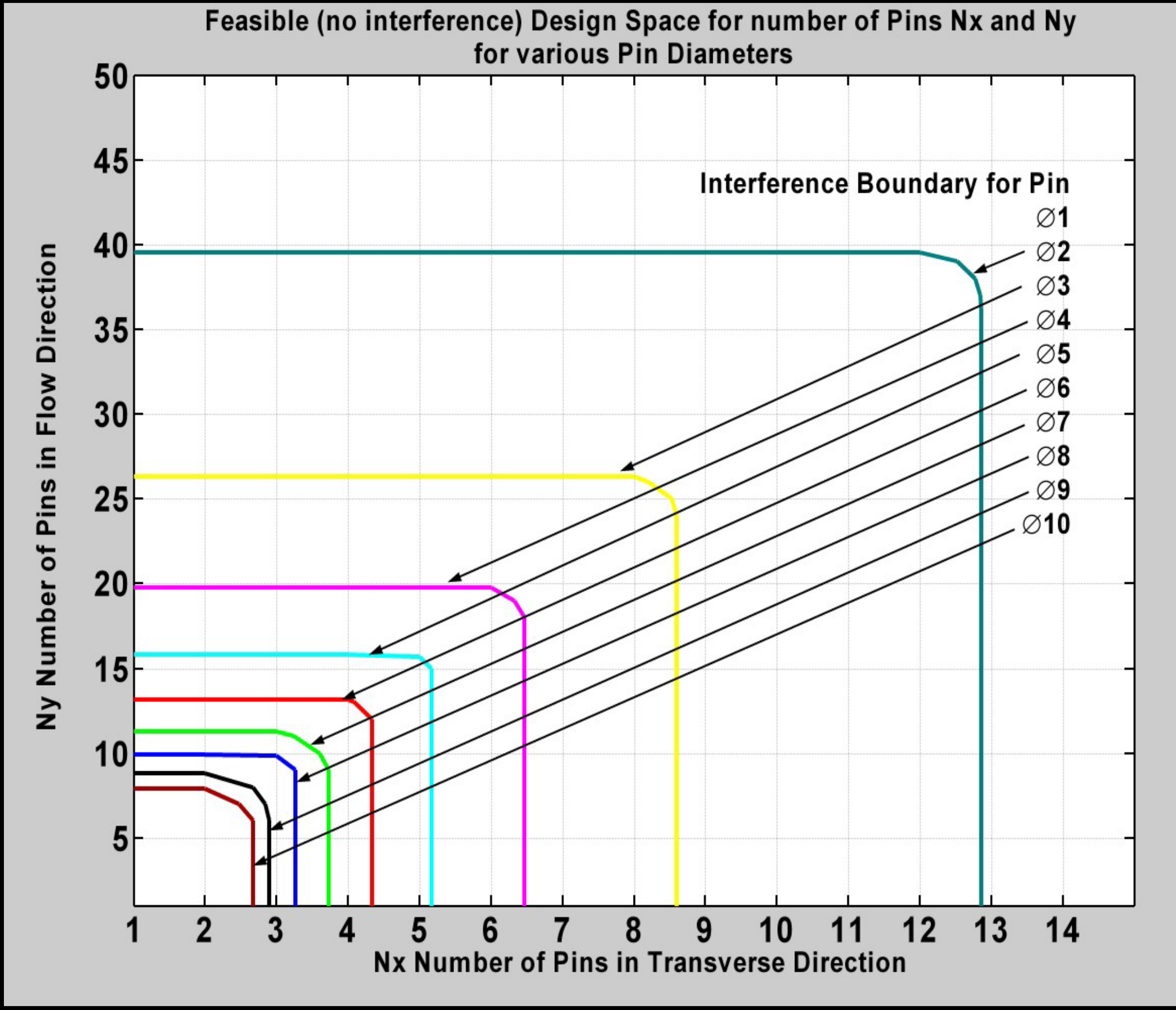
Pressure Drop

$$\Delta P = f\,\frac{\rho U_{\max}^2}{2}\,N$$

Parametric FEA Model

Rapid Analysis of Many Different Designs





Parametric FEA Model

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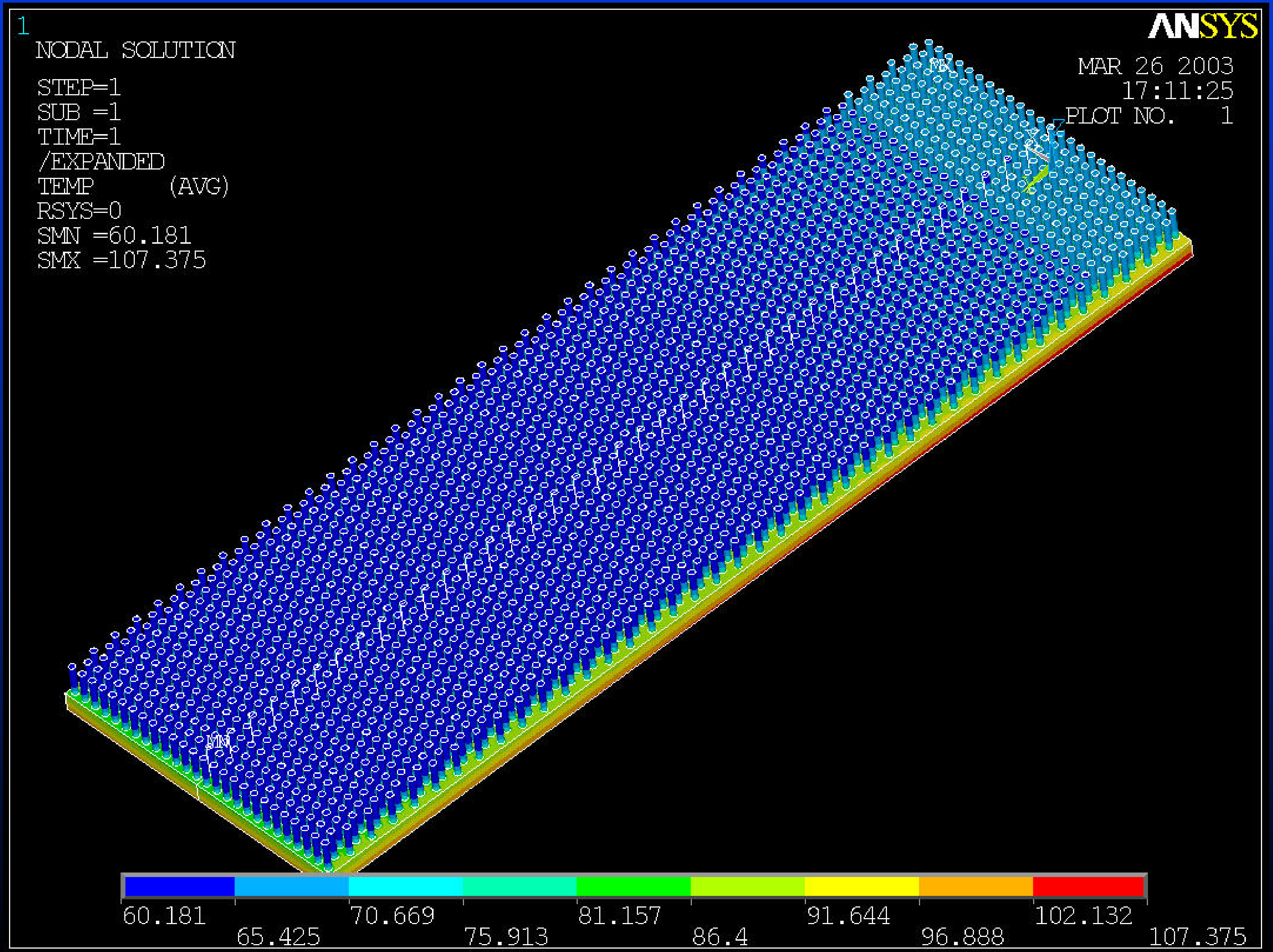

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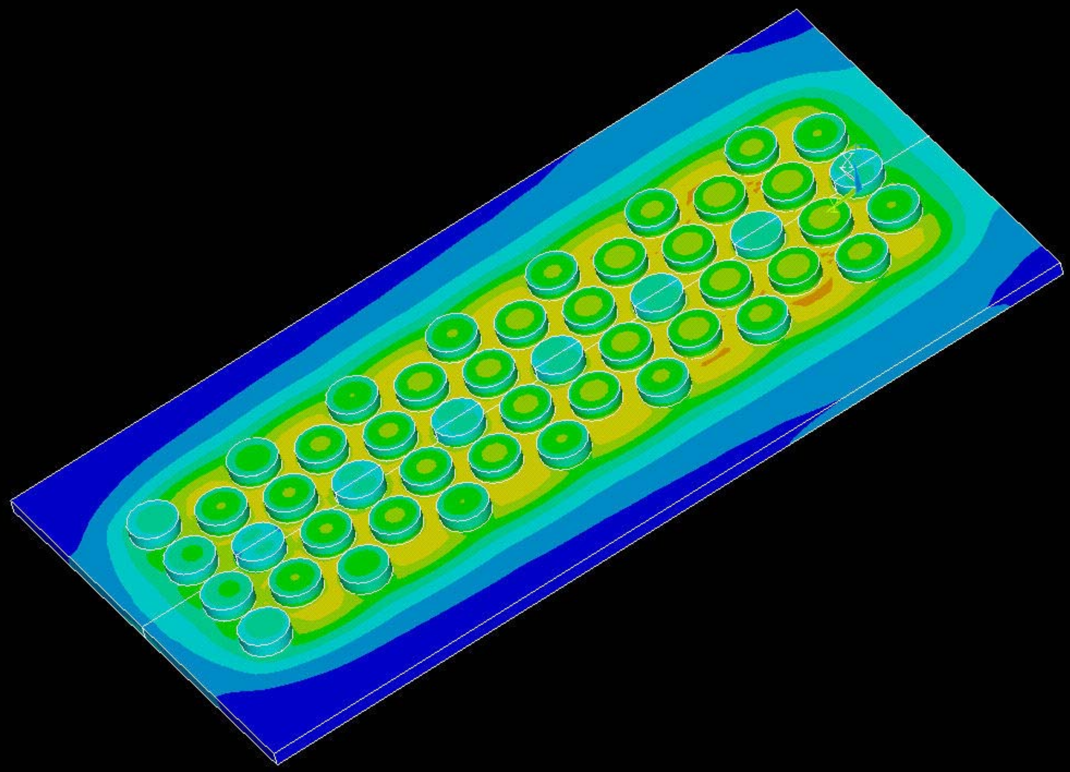

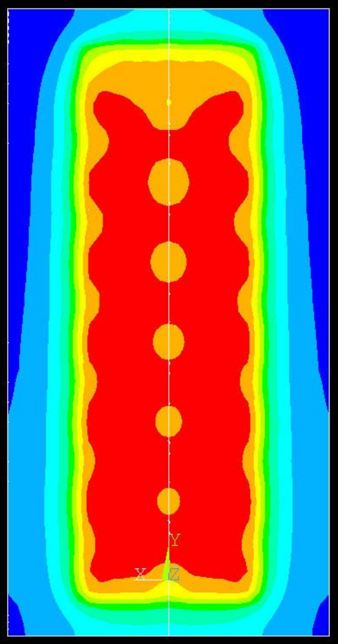

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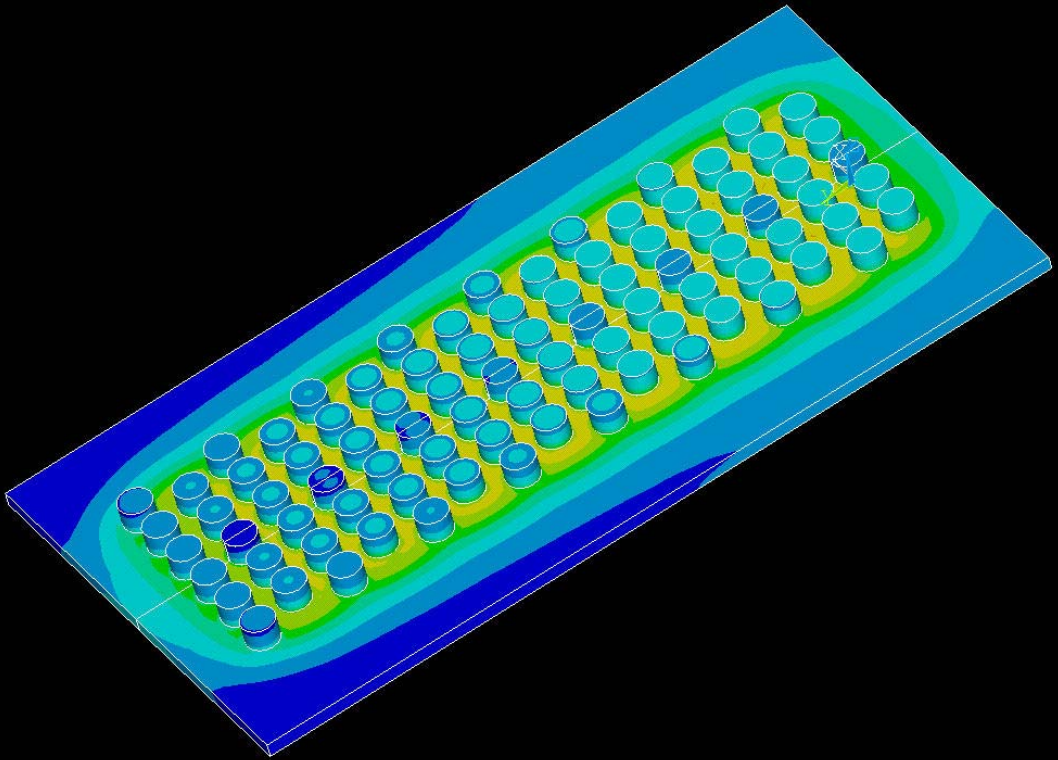

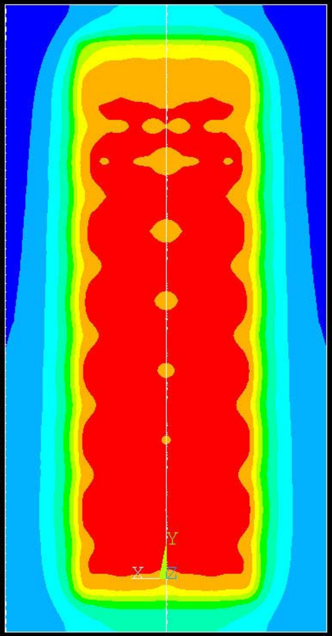

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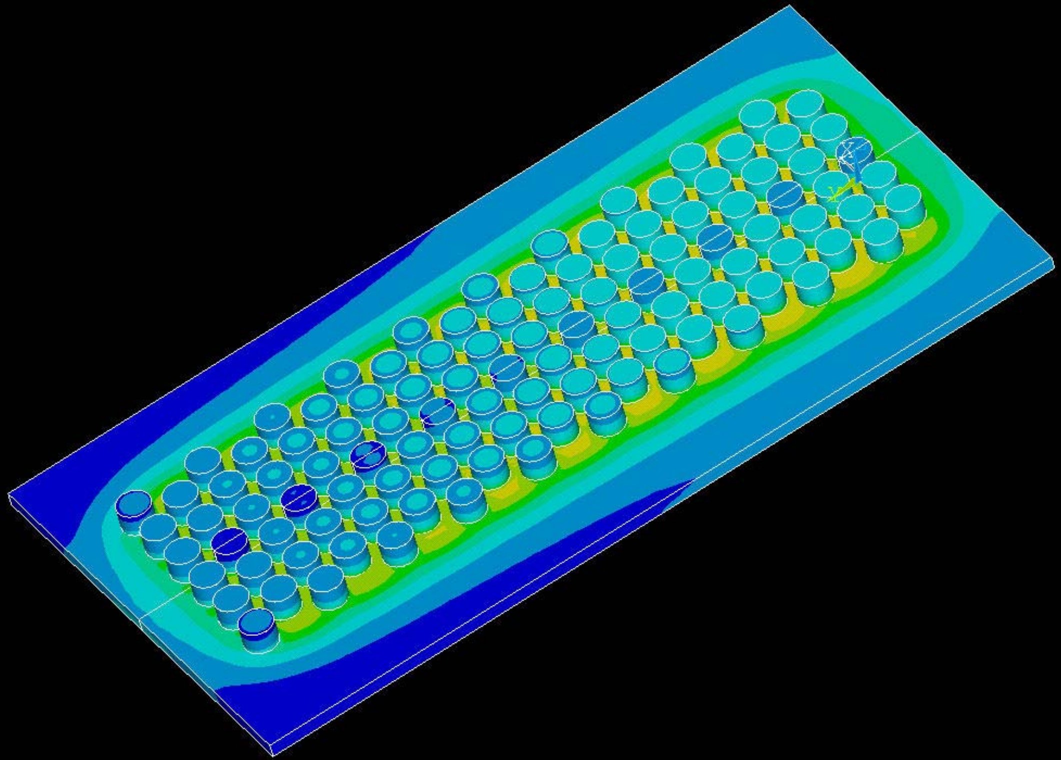

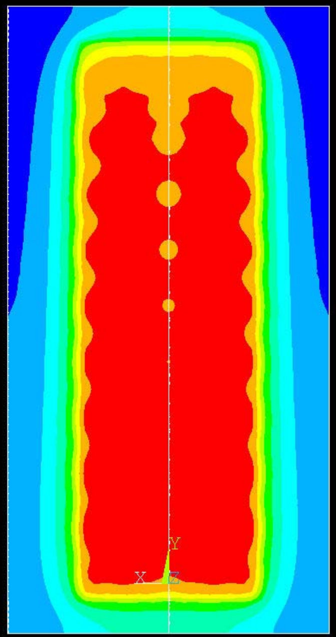

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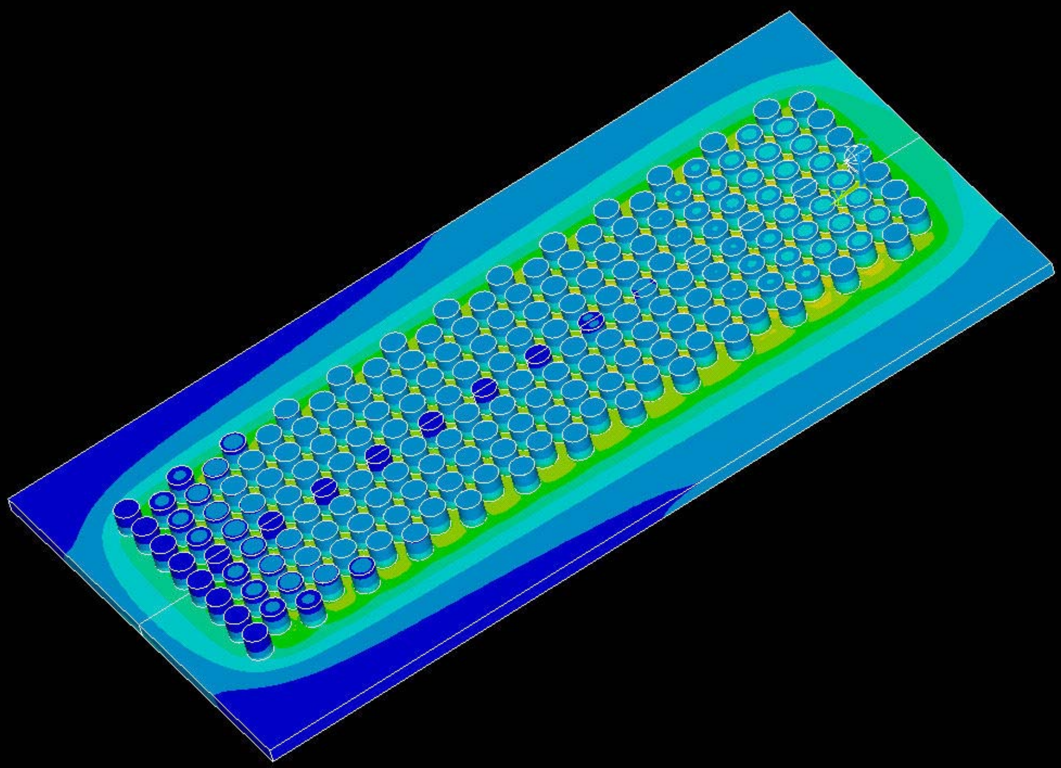

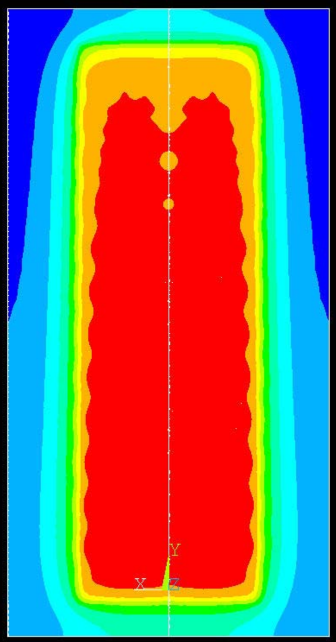

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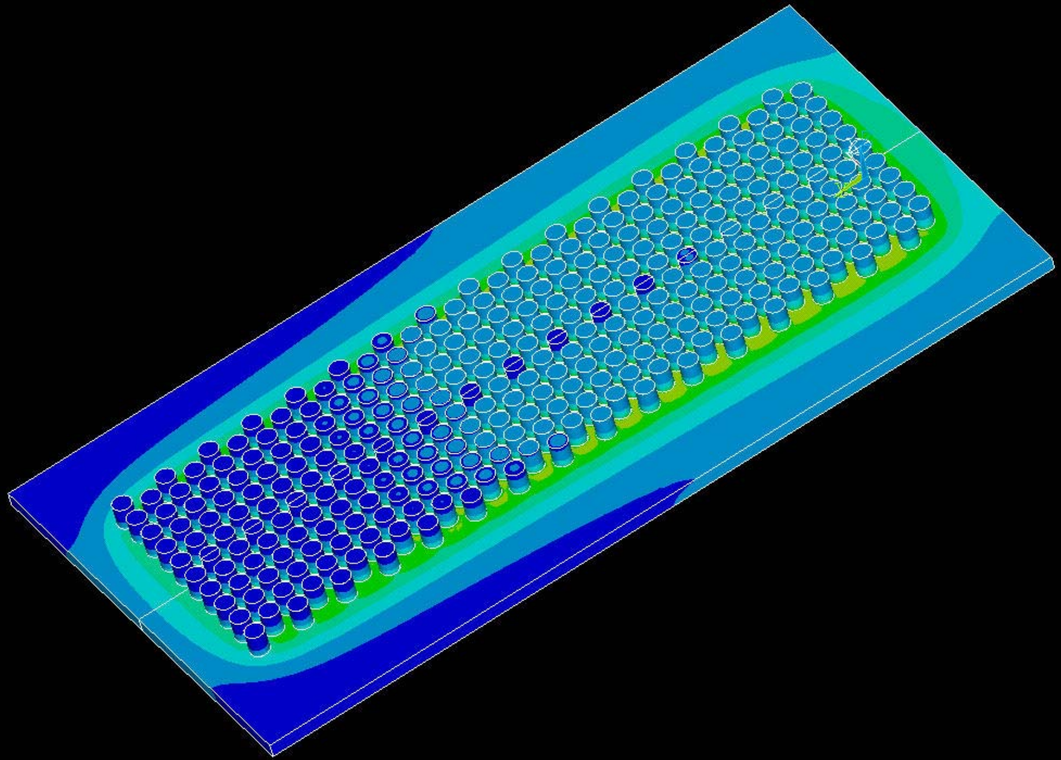
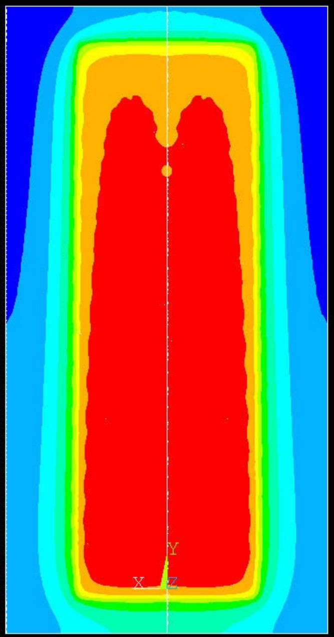
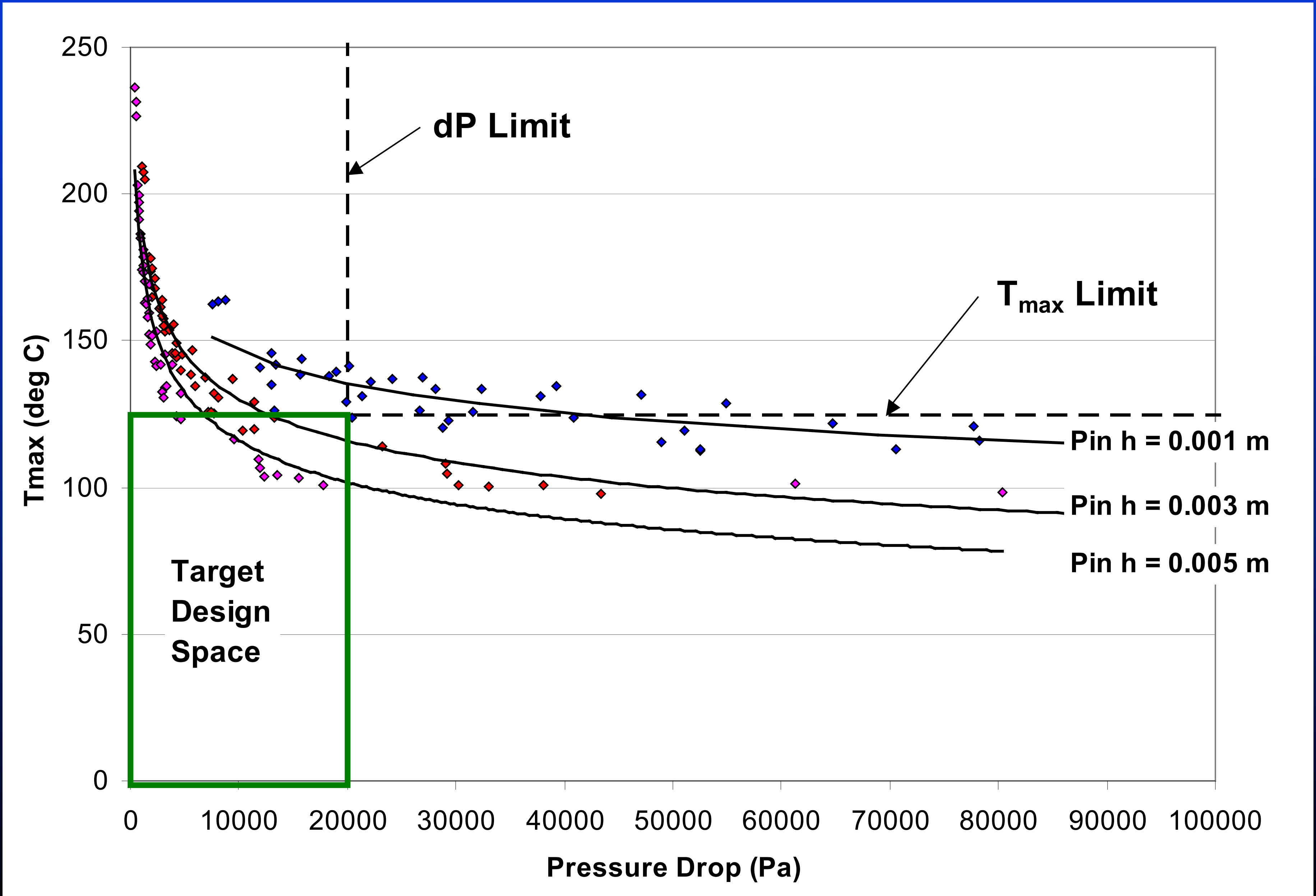




Design Space Exploration *(pin h, pin dia, spacing)*

Maximum Temperature vs. Pressure Drop



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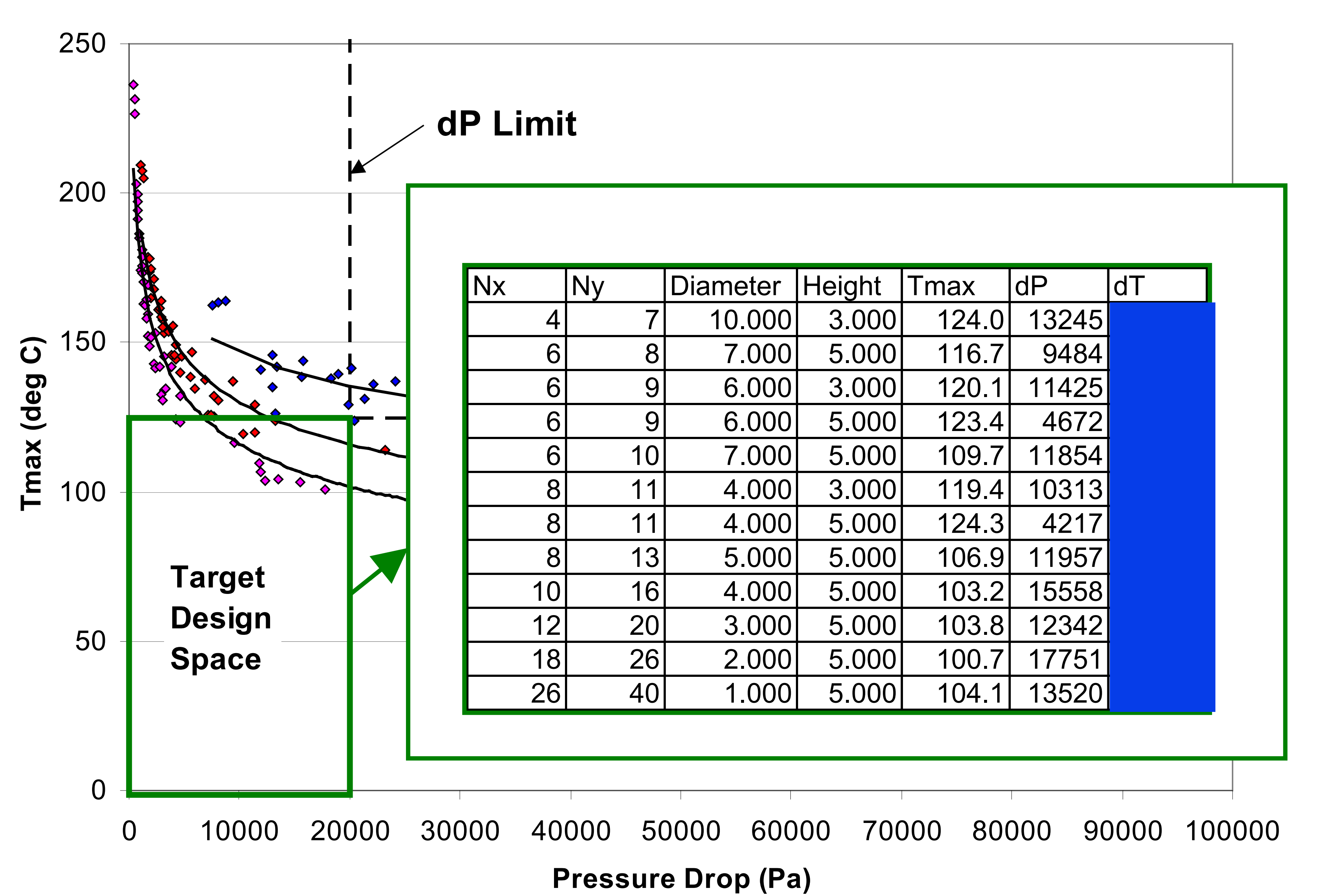
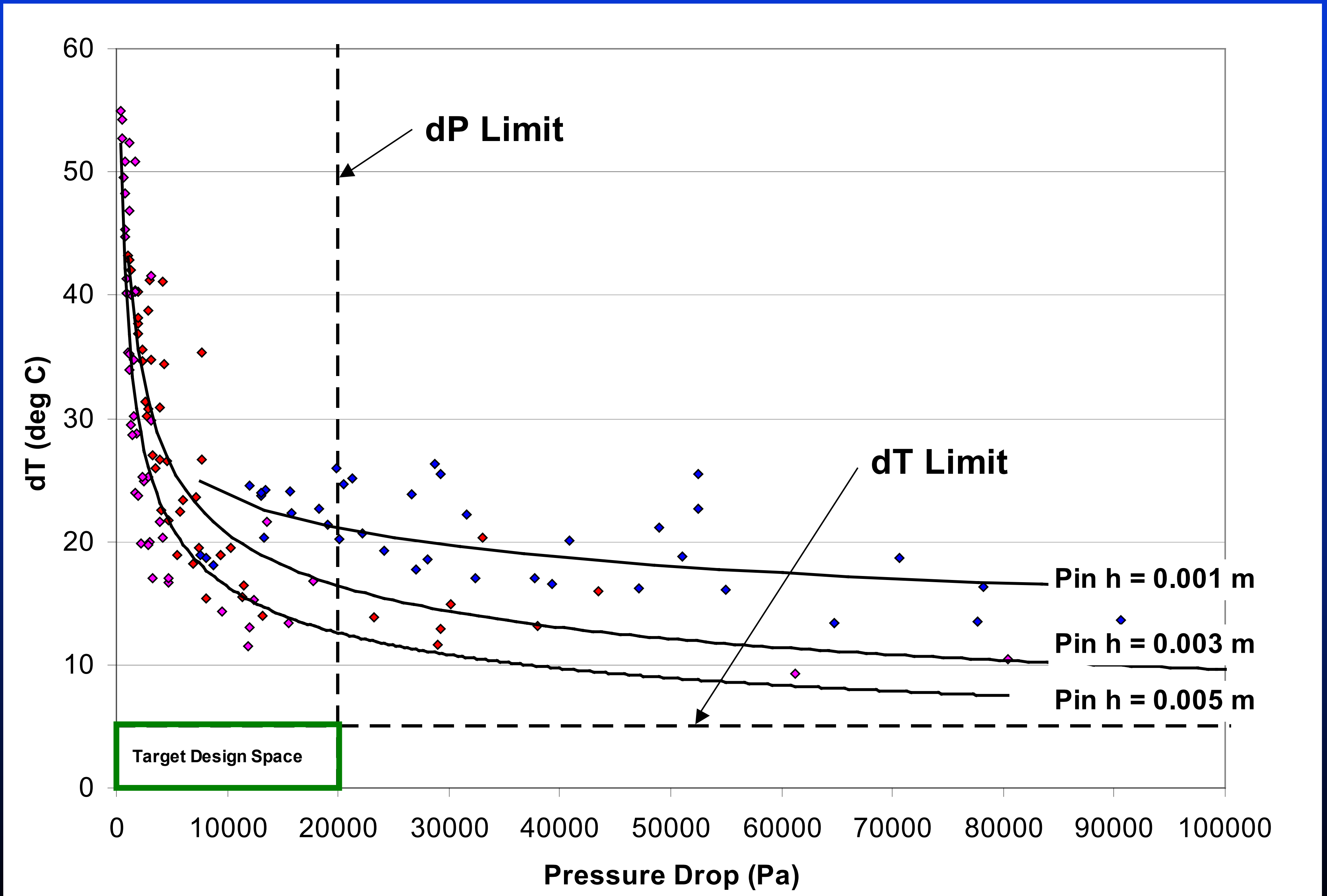


Nx	Ny	Diameter	Height	Tmax	dP	dT
4	7	10.000	3.000	124.0	13245	
6	8	7.000	5.000	116.7	9484	
6	9	6.000	3.000	120.1	11425	
6	9	6.000	5.000	123.4	4672	
6	10	7.000	5.000	109.7	11854	
8	11	4.000	3.000	119.4	10313	
8	11	4.000	5.000	124.3	4217	
8	13	5.000	5.000	106.9	11957	
10	16	4.000	5.000	103.2	15558	
12	20	3.000	5.000	103.8	12342	
18	26	2.000	5.000	100.7	17751	
26	40	1.000	5.000	104.1	13520	

Design Space Exploration *(pin h, pin dia, spacing)*

Temperature Differential vs. Pressure Drop



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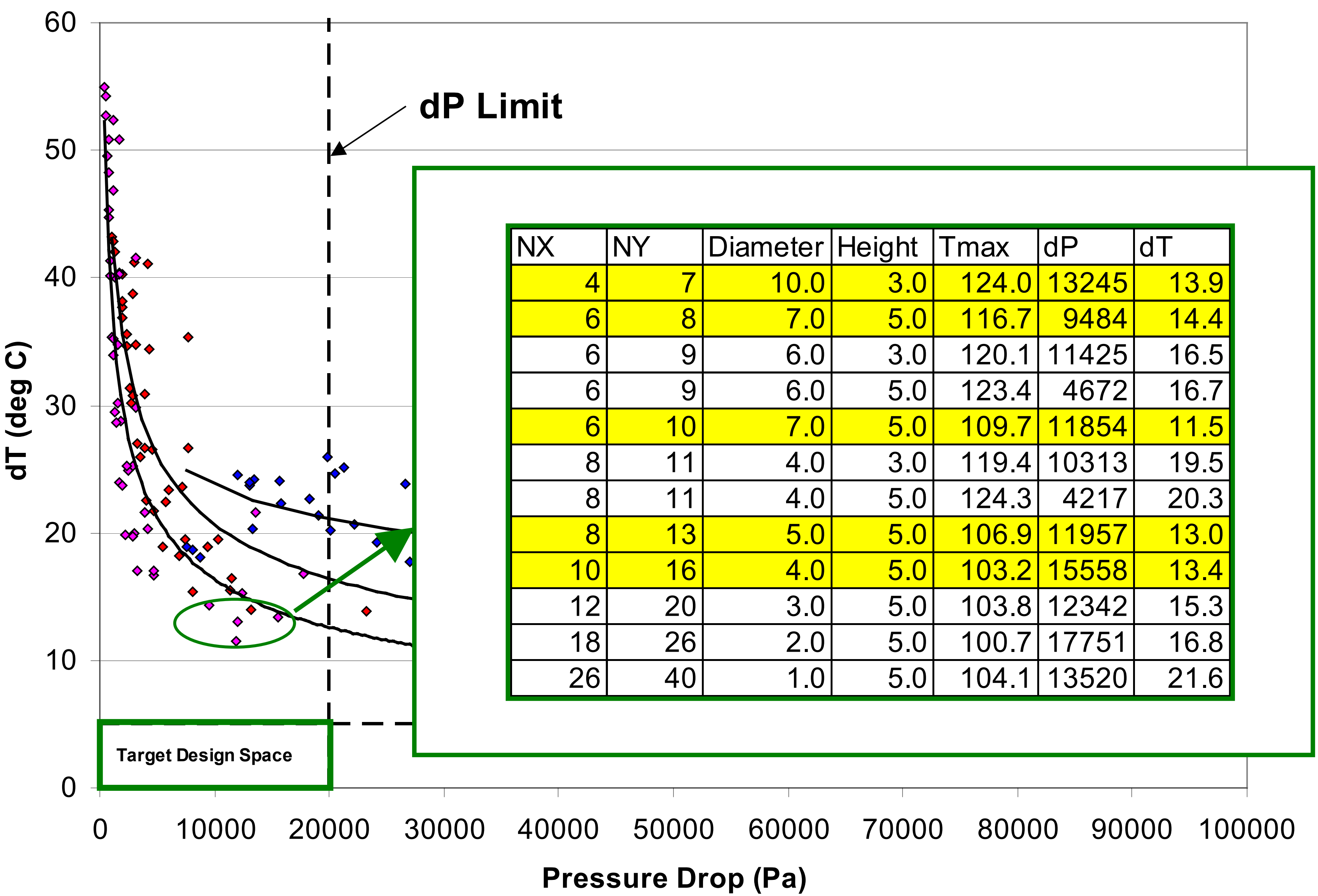
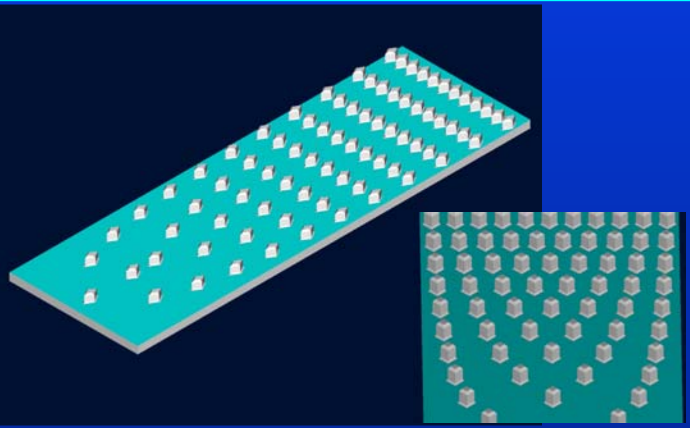
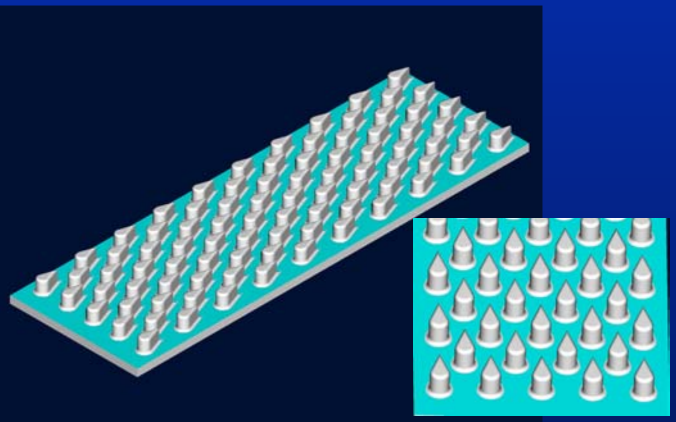
Temperature Differential vs. Pressure Drop

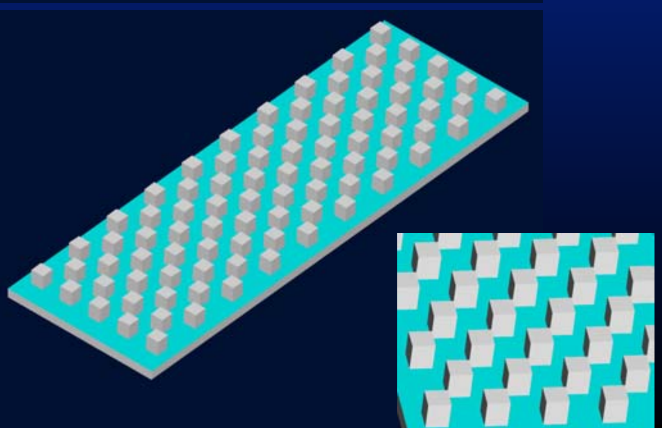


NX	NY	Diameter	Height	Tmax	dP	dT
4	7	10.0	3.0	124.0	13245	13.9
6	8	7.0	5.0	116.7	9484	14.4
6	9	6.0	3.0	120.1	11425	16.5
6	9	6.0	5.0	123.4	4672	16.7
6	10	7.0	5.0	109.7	11854	11.5
8	11	4.0	3.0	119.4	10313	19.5
8	11	4.0	5.0	124.3	4217	20.3
8	13	5.0	5.0	106.9	11957	13.0
10	16	4.0	5.0	103.2	15558	13.4
12	20	3.0	5.0	103.8	12342	15.3
18	26	2.0	5.0	100.7	17751	16.8
26	40	1.0	5.0	104.1	13520	21.6

Behavioral Modeling within the CAD Environment







- Attribute driven Parametric modeling (dP, Tmax, dT)
- Automated optimization at the design stage
- Very fast solutions and flexible geometry
- Requires closed form solutions or link to other analysis tool (CFD, FEA, etc.)

Summary and Conclusions

- **Computational Fluid Dynamics**
  - Detailed model allows flexibility
  - Computationally and time intensive solutions (hours)
  - Excellent for flow visualization, validation, and limited investigations
- **Thermal FEA with Heat Transfer Coefficients from CFD**
  - Allows for smaller CFD model (solution still may take hours)
  - Thermal model yields solutions quickly (minutes)
  - Requires CFD run for each new design configuration
- **Thermal FEA with Theoretical Determination of h & dP:**
  - Fast solutions (minutes) that can be linked with optimization techniques
  - Requires closed form solution for h and dP
- **Behavioral Modeling within the CAD Environment**
  - Very fast solutions (seconds)
  - Excellent for optimization
  - Requires a closed form solution, or link to another analysis tool (CFD, thermal)

Summary and Conclusions

- Rapid optimization of pin fin geometry can be achieved using parametric thermal FEA with theoretical determination of heat transfer coefficients and pressure drop

- Integrated, liquid-cooled pin-fin heat exchanger was effective for achieving the target maximum temperature and pressure drop

- Achieving a uniform temperature distribution (lower dT) will require more detailed optimization of coolant flow path - such as variable pin spacing

Future Directions

- Compare Analysis with Experimental Results
- Apply Probabilistic techniques to evaluate the effect of variations in
  - flow rate,
  - heat generation rates,
  - inlet coolant temperature, etc.
- Investigate other geometric alternatives
  - Pin Geometry
  - Variable pin spacing
  - Flow path
- Investigate other cooling techniques
  - Heat pipes
  - Carbon Foam
  - Di-electric Cooling